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INVENTOR: Vivek A. Jairazbhoy
Jay D. Baker
Lawrence L. Kneisel
Myron Lemecha
Prathap A. Reddy

TITLE: Evaporative Cooling Device And Method

ATTORNEY: Jeffry M. Nichols, Esq.
BRINKS HOFER GILSON & LIONE
P.O. BOX 10395
CHICAGO, ILLINOIS 60610
(312) 321-4200

EVAPORATIVE COOLING DEVICE AND METHOD

BACKGROUND

The invention relates generally to cooling devices for transferring heat from an electronic device, for example, or other item to be cooled. More specifically, the invention relates to devices that use evaporative cooling to spread heat and lower temperature of electronic devices.

Cooling of electronic devices is sometimes necessary to ensure their proper operation, reliability and useful life. Such temperature control is especially critical in severe environments, including automotive, transportation and industrial electronic applications. In electronic applications, electronic components are placed close to other heat generating components to decrease the overall size of the system.

Heat spreading and heat sinking are common techniques used in the electronics industry to remove heat from power generating components. A heat spreader accepts thermal energy from a source over a small area, and transports this heat to other exterior surfaces having a larger surface area. These surfaces are often connected directly or indirectly to a heat sink. Heat sinks typically have a large thermal mass and a finned or otherwise contoured exterior surface to dissipate heat to the ambient environment. The dissipation of heat into the ambient environment is usually the rate limiting thermal transport step, because the ambient environment (typically air or a relatively poorly conducting liquid) is a poor thermal conductor. Therefore, a heat spreader to heat sink contact area is larger than the heat source to heat spreader contact area to enhance the surface area available for dissipation.

In some applications, the heat sink is designed to also serve as a heat spreader.

A common type of heat spreader is a solid plate or block of highly conductive metal that conducts the heat. To conduct heat at an adequate rate, the material of the heat spreader is highly conductive and transports heat through a large cross-section having a minimum thickness. In some applications, the heat is transferred from the electronic device to a cooling conduit that contains air or liquid and then to the air or liquid within the cooling conduit. The heat is carried away from the electronic device by the air or liquid in the conduit.

There are known methods to transfer heat from an electronic device to air or liquid within a cooling conduit using a heat spreader. If the cooling conduit is not thermally conductive, a solid metal heat spreader may be placed directly in the air or liquid. In one example, a "cut-out" is made in the wall of the cooling conduit, and the heat spreader is partially inserted into the "cut-out." The "cut-out" is then sealed.

The "cut-out" method, however, does not create annular thermal contact between the heat spreader and cooling conduit. Therefore, the "cut-out" method has a lower thermal efficiency. Further, solid heat spreaders can create a thermal mismatch between the heat spreader and the electronic component being cooled. This thermal mismatch can adversely affect the reliability of the component and/or the fatigue life of the solder.

Solid heat spreaders have several more disadvantages. They can add weight to a system. When solid heat spreaders are attached circumferentially

to a cooling conduit made of conductive material, the contact resistance between the spreader and the cooling conduit (improved by thermal grease) adversely affects thermal efficiency. Further, solid heat spreaders require an independent insulating element that isolates electrical communication between the electronic device and the heat sink.

Another type of heat sink is a chamber completely filled with a liquid. As heat is transferred to the liquid from the electronic device, the liquid re-circulates by natural convection due to a temperature differential and gravity, thereby spreading heat away from the electronic device. This type of heat spreader has significant limitations including: (1) restriction to specific orientations due to the reliance on gravitational re-circulation, (2) reliability concerns due to a mismatch between the operating liquid and the enclosing chamber, (3) performance limitations if the operating liquid is a poor heat conductor, and (4) poor 2-dimensional/3-dimensional spreading capability since the circulation is gravity driven.

Another heat transport device is a heat pipe. The heat pipe transports heat from one location to another by: (1) vaporizing a liquid at the hot (evaporator) end, (2) transporting the vapor, and hence the latent heat of vaporization, to the cold (condenser) end by advection within the device, (3) condensing the liquid by giving up heat to the condenser, and (4) returning the condensate either by gravity or capillary action to the evaporator.

Heat pipes typically distribute heat in 1-dimension. The primary function is to transport heat from the source to a remote location with limited heat spreading. In addition, capillary wick structures in a typical heat pipe

extend all around the periphery of the device, generally resulting in an electrical path between the evaporator and condenser regions. Thus, when used for the cooling of electronic devices, an independent electrical insulator is used.

BRIEF SUMMARY

The present invention is designed to better spread heat to a heat sink, such as a cooling conduit. A container defines an annular chamber that is partially filled with a liquid coolant. Heat generated by an electronic device is transferred to the liquid coolant within the chamber and causes the liquid coolant to boil. The vaporized coolant rises away from the electronic device carrying the latent heat of vaporization. The vaporized coolant substantially condenses on and near surfaces within the container cooled by a cooling conduit, and the heat is transferred to the air or liquid within the cooling conduit. The condensed coolant travels back toward the electronic device via gravity and/or a wick structure.

In a first aspect, the invention comprises a container having a receptacle for receiving an electronic device. The container: (1) defines a chamber that is partially filled with a liquid coolant, (2) is capable of receiving a cooling conduit, and (3) contains a wick structure.

In a second aspect, the invention comprises a receptacle having a first and a second surface. The first surface is capable of being connected to an electronic device, and the second surface is connected to a wick. The wick structure may be saturated in a coolant and has at least one ambient vent.

In a third aspect, the invention comprises a container having a receptacle for receiving an electronic device. The container has an inner wall and an outer wall, and defines an annular chamber. The container is partially filled with a liquid coolant such that the liquid coolant does not contact both the inner wall and the outer wall simultaneously.

In a fourth aspect, the invention comprises providing a container having a receptacle for receiving an electronic device, the container defining a chamber and having an inner wall and an outer wall; filling the container partially with a liquid coolant such that the liquid coolant does not contact both the inner wall and the outer wall simultaneously; providing an electronic device; connecting the electronic device to the receptacle of the container; generating heat by the electronic device; transferring heat to the coolant; connecting a cooling conduit to the container; and, forcing air or liquid through the cooling conduit.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

FIG. 1A is side view of one embodiment of an evaporative cooling device positioned around a cooling conduit.

FIG. 1B is a cross-sectional view taken generally along line A-A of FIG. 1A.

FIG. 2A is top view of one embodiment of an evaporative cooling device positioned between cooling conduit segments.

FIG. 2B is a cross-sectional view taken generally along line A-A of FIG. 2A.

FIG. 2C is a cross-sectional view taken generally along line B-B of FIG. 2A.

FIG. 3A is a side view of one embodiment of an evaporative cooling device positioned within a cooling conduit.

FIG. 3B is a cross-sectional view taken generally along line A-A of FIG. 3A.

FIG. 4A is a side view of another embodiment of an evaporative cooling device positioned within a cooling conduit.

FIG. 4B is a cross-sectional view taken generally along line A-A of FIG. 4A.

FIG. 5 is side view of one embodiment of an evaporative cooling device positioned in contact with a coolant main.

FIG. 6 is side view of one embodiment of an evaporative cooling device positioned in contact with a coolant main.

FIG. 7A is top view of one embodiment of an evaporative cooling device positioned in contact with a coolant main.

FIG. 7B is a cross-sectional view taken generally along line A-A of FIG. 7A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIGS. 1-7 show an evaporative cooling device for cooling an electronic component. The evaporative cooling device shown in FIGS. 1A and 1B represents a first embodiment.

An electronic device 101 is attached to a receptacle 102. The receptacle 102, which is a heat spreader, is connected to a container 113. The container 113 has an outer wall 108, an inner wall 107, and two side walls (not pictured). The container 113 defines an annular chamber 111 that is partially filled with a liquid coolant (not pictured). The inner wall 107 defines an annular region 103.

The container 113 may be of any shape as long as an annular volume is included in the annular chamber 111 and it is capable of receiving a cooling conduit. The term "annular" as used herein is not limited to any particular shape. Rather, "annular" means a continuous ring, e.g. a square, circle, triangle or any other continuous geometric shape. The shape and dimensions of the container 113 are determined based on the shape and dimensions of the cooling conduit that the evaporative cooling device is designed to receive, ease of manufacturing, minimization of materials, structural integrity or other design criteria.

The electronic device 101 may be directly placed on the container 113 or on an intervening heat spreader receptacle 102 that is connected to the container 113. If the electronic device 101 is placed directly on the container 113, it may be placed anywhere and in any orientation on the container 113, although the electronic device 101 should be attached so as to maximize heat transfer, such as adjacent a wall in contact with liquid coolant.

A first wick structure 110 lines the inside of the outer wall 108, and a second wick structure 109 lines the inside of the inner wall 107 (the term "inside" refers to "in" the container 113). A communicating wick structure 104

periodically connects the first wick structure 110 and the second wick structure 109. The shape of the communicating wick structure can be cylindrical, rectangular, or any other suitably shaped beam.

In addition, condenser plates 114 are connected to the inner wall 107 of the container 113 and are periodically located within the annular chamber 111 to promote condensation of vaporized coolant over the entire annular chamber 111. The container 113 also contains flow dividers 105. The flow dividers 105 can completely or incompletely split the flow of vaporized coolant into two streams as vapor circulates around the annular region 103 and the inner wall 107. The flow dividers 105 promote more uniform heat spreading and improve the efficiency of condensation.

The container 113, condenser plates 114, and receptacle 102 are made out of a highly conductive material, such as copper, aluminum, stainless steel, aluminum oxide, or beryllium oxide.

One or more of the wick structures may be removed or not used. The condensed liquid coolant can be returned toward the electronic device by gravity. Alternatively, in applications where orientation of the device is not stable, a wick structure may be used to facilitate return of the liquid coolant. In such situations, any embodiment of wick structure may be employed as long as the wick structure provides a passage for liquid coolant to return toward the electronic device. Similarly, corresponding wick structures are not necessary where there is an available path for the condensed liquid coolant to return toward the electronic device, i.e. the condensed coolant can travel toward the electronic device by gravity or via the first and/or second wick

structures. In further embodiments, flow dividers are not used or different, additional or fewer flow dividers are used.

The annular region 103 is capable of receiving a cooling conduit 115 so that the container 113 surrounds the cooling conduit 115, and the inner wall 107 of the container 113 is flushed against the outside wall 116 of the cooling conduit 115. The term "flushed" means directly abutting or immediately adjacent. Cool air or liquid may be forced through the cooling conduit 115 to provide a heat sink. This embodiment is most appropriate when the wall of the cooling conduit 115 is thermally conductive, such as a structural member, e.g. a metal cross-car beam.

The outside wall 116 of the cooling conduit 115 and the inner wall 107 of the container 113 may each be microscopically uneven so that these two surfaces may not be positioned entirely flush against each other when the container 113 receives the cooling conduit 115. A thermally conductive material may be interposed between these two surfaces to fill in the microscopic gaps and enhance heat transfer. Examples of a conductive material include a metal oxide filled, silicone free synthetic grease. Alternatively, the evaporative cooling device of the present invention may be constructed so that the inner wall 107 of the container 113 is the outside wall 116 of the cooling conduit 115. In this alternative, vaporized coolant mostly condenses on the outside wall 116 of the conduit 115.

The liquid coolant is not generally thermally conductive. Examples include methanol, glycol, water, ammonia, acetone, methyl alcohol, freon or a mixture thereof, or other suitable substances known to those skilled in the art.

The particular materials of the container and liquid coolant are chosen in accordance with the operating temperature requirements in which the container assembly is to be used.

Various amounts of liquid coolant may be added to the container. An amount may be added to form a coolant pool near the electronic device, or where a wick structure is present near the electronic device, an amount may be added to completely or incompletely saturate the wick structure. In one embodiment, the inner wall 107 does not contact the coolant pool. The inner wall 107 is not partially submerged in the coolant pool (i.e. the liquid coolant pool does not contact both the inner wall 107 and the outer wall 108 simultaneously). Alternatively, a portion of the inner wall 107 may be in contact with the coolant pool.

A liquid coolant pool is not formed in those embodiments with a wick structure lining the inside of the outer wall 108, because the liquid coolant saturates the wick structure. Since no coolant pool is formed, the liquid coolant does not contact both the inner wall 107 and the outer wall 108 simultaneously.

The flow dividers 105 and wick structures 104, 109, 110 can be composed of a screen mesh, metal fiber, crushed copper felt, partially fused plastic beading material or other porous material, such as a porous, sintered, or powdered metal, a ceramic material, or other material capable of returning the condensed liquid coolant toward the electronic device 101. This return is accomplished primarily by way of capillary forces, but also by forces generated by the static head of the liquid coolant.

In operation of the embodiment shown in FIGS. 1A and 1B, heat generated by the electronic device 101 causes boiling of the liquid coolant within the container 113. The vaporized coolant rises away from the electronic device 101 and spreads throughout the annular chamber 111. The latent heat of vaporization is removed by condensation. The vaporized coolant condenses substantially on the inner wall 107 of the container 113 and the condenser plates 114 because these surfaces are cooled by the cooling conduit 115. The heat mostly transfers to the air or liquid in the cooling conduit 115. After condensation, the liquid coolant returns toward the electronic device 101 by gravity and/or by capillary wick action via the first, second, and/or communicating wick structures 110, 109, 104.

Another embodiment is shown in FIGS. 2A-C. An electronic device 201 is attached to a container 202 at a receptacle 218. The term “receptacle” as used herein means a surface capable of receiving an electronic device. The receptacle may be part of the container as in FIGS. 2A, 2B, and 2C, or it may be an intermediate heat spreader as in FIGS. 1A and 1B.

The container 202 defines an annular chamber 207 that is partially filled with a liquid coolant (not pictured). The container 202 contains flow dividers 212. The container 202 has an outer wall 209, an inner wall 208, and two side walls 219. A first wick structure 210 lines the inside of the outer wall 209 and a second wick structure 211 lines the inside of the inner wall 208. The inner wall 208 defines an annular region 213. In this embodiment, the inner wall 208 extends beyond the side walls 219, and forms annular edges

214, 215. Each side of the container 202 has an edge 214,215, and each edge 214, 215 is capable of receiving a cooling conduit segment 204, 205.

The materials, shapes and other aspects of various components described with respect to the embodiment shown in FIGS. 1A and 1B are applicable to other embodiments, so will not be repeated for other embodiments.

In operation, cooling conduit segments 204, 205 are placed on edges 214, 215 so that the walls 216, 217 of the cooling conduit segments 204, 205 fit around the edges 214, 215 and flush against the side walls 219. To facilitate an easy fit, the cooling conduit segments 204, 205 may be made of a rubber-like material. If the seal is not air or liquid tight, clamps 203 or any other fastening means may be used to secure the cooling conduit segments 204, 205 to the container 202. Other methods of connecting the cooling conduit segments 204, 205 to the edges 214, 215 are readily known to those skilled in the art. For example, the edges 214, 215 may be constructed so that the cooling conduit segments 204, 205 may be inserted into the annular region 213 via edges 214, 215.

After cooling conduit segments 204, 205 are securely fastened, air or liquid may be forced through the first cooling conduit segment 205, through the annular region 213 of the container 202 and into the second cooling conduit segment 204. Heat generated by the electronic device 201 is transferred to liquid coolant within the container 202 and boils the liquid coolant. The vaporized coolant rises away from the electronic device 201. The inner wall 208 is cooled by the air or liquid flowing through the annular

region 213. Vaporized coolant spreads around the annular chamber 207 and condenses on or near the inner wall 208. The condensing coolant dissipates heat to the air or liquid in the annular region 213. The condensed coolant returns toward the electronic device 201 via gravity and/or the first and second wick structures 210, 211.

FIGS. 3A, 3B, 4A and 4B show other embodiments. These embodiments are most appropriate when the "cut-out" method is used. An electronic device 301 is attached to a receptacle 302. The receptacle 302 is attached to a container 313 that defines an annular chamber 306. The container has an outer wall 314, an inner wall 315, two side walls (not pictured), and a base 309. The inner wall 315 defines an annular region 308.

The container 313 is lined with a first wick structure 312 lining the inside of the outer wall 314 and a second wick structure 311 lining the inside of the inner wall 315. Communicating wick structures 305 periodically connect the first and second wick structures 312, 311. The container also includes a flow divider 314.

As shown by FIG. 3B, the base 309 has a width less than the receptacle 302. Therefore, the base 309 does not cover the receptacle 302 entirely and portions 316 of the receptacle 302 on each side of base 309 are not covered by the container 313.

As noted above, this embodiment is most appropriate in the "cut-out" method. An aperture may be created in a wall 303 of a cooling conduit 317. The size of the aperture depends on the size of the receptacle 302. The area of the cooling conduit 317 removed or created substantially equals the area of

the receptacle 302. The container 313 may be placed within the cooling conduit 317 via the aperture in the cooling conduit wall 303. The receptacle 302 is capable of receiving the cooling conduit such that the receptacle 302 forms part of the cooling conduit wall 303. The receptacle 302 covers the aperture and may be sealingly connected to the cooling conduit 317 such that the seal is air and/or liquid tight. Alternatively, if the receptacle 302 does not cover the aperture in the cooling conduit wall 303, a filler may be used to fill any gap between the cooling conduit wall 303 and the receptacle 302. After the receptacle 302 is sealingly attached to the cooling conduit wall 303, air or liquid may be forced through the cooling conduit 317.

The cooling conduit wall 303, the outer wall 314, and the portions 316 of the receptacle 302 define a U-shaped region 307. In operation, heat generated by the electronic device 301 is transferred to the liquid coolant near the base 309 of the container 313. The heat causes the liquid coolant to boil and the vaporized coolant vapor rises away from the electronic device 301. Unlike the embodiments shown earlier, the vaporized coolant condenses substantially on both the inner wall 315 and the outer wall 314. Forced air or liquid flows within both the first annular region 308 and the U-shaped region 307 and cools both the inner and outer walls 315, 314. The heat is transferred from the coolant to the air or liquid within the cooling conduit 317 and flowing through the annular region 308 and the U-Shaped region 307. The condensed coolant is returned toward the electronic device 301 via the first and second wick structures 312, 311 and communicating wick structures 305, and/or gravity.

FIGS. 4A and 4B illustrate another embodiment. A flow separator 310 is included in the container 313. The flow separator 310 separates the flow of vaporized coolant within the annular chamber 306 into two paths. One path of the flow is directed closer to the outer wall 314 of the container 313, and one path is directed closer to the inner wall 315 of the container 313.

Suitable materials for the flow separator 310 are the same as or similar to the materials described above with respect to the wick structures and the flow dividers. The flow separator promotes condensation by partially or fully blocking the vapor from flowing only to one side the container 313. This leads to a greater distribution of the vapor and more area is available for the vapor to condense.

In operation, heat generated by the electronic device 301 is transferred to the liquid coolant and boils the coolant. The vaporized coolant then substantially travels one of two paths. The vaporized coolant travels the path indicated by arrow 317 and corresponding arrows (closer to the outer wall 314) or the path indicated by arrow 316 and corresponding arrows (closer to the inner wall 315). The vaporized coolant then condenses on the inner and outer walls 315, 314 depending on the path the vaporized coolant traveled. The air or liquid flowing in the cooling conduit 317 flows through the annular region 308 and the U-shaped region 307 and carries away heat transferred from the vaporized coolant.

The embodiments discussed above: (1) may have a higher efficiency and heat removal capacity than traditional solid heat spreading systems, so may be smaller in size, lighter weight, and correspondingly lower in cost; (2)

may provide electrical isolation, obviating the use of electrical insulators that conduct heat poorly; (3) may be more reliable because of a less dominant thermal mismatch (lower contact resistance) between the heat spreader and the electronic component; and (4) in the "cut-out" embodiment, may have an annular, high surface area contact unlike current "cut-out" devices and methods.

Another embodiment is shown in FIGS. 5 and 6. An electronic device 503 is attached to a first surface of a receptacle 504. A wick structure 506 attaches to a second surface of the receptacle 504. Ambient vents 505 are included within the wick structure 506 . The wick structure 506 is attached to a coolant main outlet 507. The coolant main outlet 507 projects from a coolant main 501. The coolant main 501 communicates with a liquid coolant pool (not pictured). A regulator 502 attaches to the coolant main outlet 507.

The regulator 502 regulates the flow of coolant from the coolant main 501 through the coolant main outlet 507 and to the wick structure 506. The regulator 502 can be a solenoid valve that allows a volume of coolant to flow to the wick structure 506 by opening the valve aperture. The flow regulator 502 may also be temperature, conductance or capacitance controlled (i.e. different levels of saturation of the wick structure yield different levels of temperature, capacitance, and conductance).

In operation, liquid coolant is drawn from the coolant pool and flows through the coolant main 501 into the coolant main outlet 507. The liquid coolant then flows into and saturates the wick structure 506. The regulator 502 controls the degree of saturation. Heat generated by the electronic

device 503 is transferred to the receptacle 504. The heat is then transferred to the liquid coolant in the wick structure 506. The heat boils the liquid coolant. The vaporized coolant rises away from the electronic device 503 substantially via ambient vents 505 and carries away the latent heat of vaporization.

The embodiment of FIG. 6 is similar to that shown in FIG. 5 except the orientation of the evaporative cooling device is changed and a collecting vent 607 is included. The collecting vent 607 is a partially enclosed passageway that is exposed to the ambient at one end. The collecting vent 607 accepts vaporized coolant escaping from each ambient vent 505.

FIGS. 7A and 7B illustrate a further embodiment. A coolant main 701 supplies liquid coolant to coolant reservoirs 703 via coolant main outlets 702. In this embodiment, a coolant pool 706 is maintained. The amount of liquid coolant supplied to the coolant reservoirs 703 and, thus, to a wick structure 709, is controlled by a regulator 712. The coolant reservoirs 703 may be constructed of an insulative material to maintain the temperature of the liquid coolant within the coolant reservoir 703.

The coolant reservoir 703 is connected to the wick structure 709 via a passageway 713. The passageway 713 may be a coolant permeable material, a channel between the coolant reservoir and the wick structure, or any other passageway known in the art. The wick structure 709 is connected to a receptacle 708. The receptacle 708 connects to an electronic device 707. The wick structure 709 includes ambient vents 710. Although five

ambient vents 710 are pictured, any number of ambient vents may be used including no and many more than five ambient vents.

In operation, liquid coolant from the coolant main 701 flows into the coolant reservoirs 703 via coolant main outlets 702. The regulator 712 controls the level of the coolant pool 706 in the coolant reservoir 703. The liquid coolant is then communicated to the wick structure 709 via the passageway 713. The liquid coolant saturates the wick structure 709 and may form a pool on the receptacle 708.

Heat generated by the electronic device 707 is transferred to the liquid coolant through the receptacle 708. The heat causes the liquid coolant to boil. The vaporized coolant rises away from the electronic device 707 substantially via ambient vents 710 and into a vapor collecting chamber 711, carrying the latent heat of vaporization. The vaporized coolant then rises through an outer vent 705.

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and are herein described in detail. It should be understood, however, that there is no intent to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined in the appended claims.